

New Atomic Data for Doubly Ionized Iron Group Atoms by High Resolution UV Fourier Transform Spectroscopy

Peter L. Smith

Harvard-Smithsonian Center for Astrophysics

Juliet C. Pickering and A. P. Thorne

Blackett Laboratory, Imperial College, London

Abstract

Currently available laboratory spectroscopic data of doubly ionized iron-group elements were obtained about 50 years ago using spectrographs of modest dispersion, photographic plates, and eye estimates of intensities. The accuracy of the older wavelength data is about 10 mÅ at best, whereas wavelengths are now needed to an accuracy of 1 part in 10^6 to 10^7 (0.2 to 2 mÅ at 2000 Å). The Fourier transform (FT) spectroscopy group at Imperial College, London, and collaborators at the Harvard College Observatory have used a unique VUV FT spectrometer in a program focussed on improving knowledge of spectra of many neutral and singly and doubly ionized, astrophysically important, iron group elements. Spectra of Fe II and Fe III have been recorded at UV and VUV wavelengths with signal-to-noise ratios of several hundred for the stronger lines. Wavelengths and energy levels for Fe III are an order of magnitude more accurate than previous work; analysis is close to completion. *f*-values for Fe II have been published.

1. Introduction

Improvements in the quality of astrophysical spectra obtained using high resolution spectrographs on ground and satellite telescopes have highlighted inadequacies in the laboratory atomic data base needed to interpret these observations, especially in the ultraviolet (UV) wavelength region. In these spectra of hot stars, lines from doubly and singly charged species dominate. Wavelengths accurate to a few parts in 10^7 are required to allow unambiguous identification and modeling of all spectral features in highly blended spectra; transition probabilities and hyperfine structure (hfs) are also needed.

The laboratory spectroscopic database for doubly charged members of the iron group is based on measurements with spectrographs of modest dispersion. The literature covering the third spectra (*i.e.*, the spectra, denoted "III," of doubly charged ions) comprises roughly a score of papers with an average age of about forty years. Some generalizations are possible:

- the accuracy of the old data is about 10 to 20 mÅ at best, whereas wavelengths are now needed to an accuracy of 1 part in 10^6 to 10^7 (0.2 to 2 mÅ at 2000 Å).
- there are no measured intensities other than eye estimates of photographic blackening;
- there are no accurate data on hyperfine structure.

The strongest transitions in these doubly ionized spectra lie in the UV. However, it is not only the UV region that has need of improvement:

- there are no data at wavelengths longer than 2675 Å for Cr III;
- until our work on Fe III there were no data longer than 2105 Å for Fe III;
- only 2 % of the known lines of Co III are at wavelengths longer than 3000 Å.

The lack of data is not a consequence of atomic structure: Ti III, the simplest ion in the set being discussed, should have ~ 500 lines with $3000 < \lambda[\text{\AA}] < 9300$ resulting from allowed transitions between known levels.

Hfs is significant in astrophysically important odd-Z third spectra because the contribution of a transition to an absorption feature is strongly dependent on whether the line is single or the absorption is distributed among many components. Some existing data, on Mn III for example, indicate that the vast majority of the lines are either diffuse (h) or wide (w). This notation reaches near farce with some lines being noted as **hhww!** This is not the quality of data needed for modern astrophysical observations.

2. Apparatus

The Fourier transform (FT) spectrometer that we use (see Thorne *et al.* 1987, 1994) holds the world short wavelength record (~ 1350 \AA) for high resolving power spectroscopy. FT spectrometry using hollow cathode discharges in the laboratory has provided wavelengths with the accuracy required in modern astrophysics for neutral atoms and singly charged ions (Pickering 1999; Nave *et al.* 1999), but application of this method to doubly charged ions has been hindered because such ions are not efficiently created and excited in d.c. hollow cathode discharges.

Third spectra and the higher levels of second spectra have hitherto been excited only with pulsed hollow cathodes, sliding sparks, etc. The poor 'shot-to-shot' reproducibility of such sources makes them unacceptable for high quality measurements with either a scanning grating or an FT spectrometer, so most laboratory spectroscopy on pulsed sources has been done using photographic plates, which have low signal/noise ratio and poor photometric and wavelength accuracies relative to those required to support modern astronomy.

We have resolved this source/spectrometer incompatibility with the identification and construction, with support of NASA, of a light source based on a d.c. Penning discharge originally developed and studied as a VUV radiometric standard. Our preliminary studies (Smith *et al.* 1998) using it and the VUV FT spectrometer at Imperial College (IC), showed that this source strikes easily, operates steadily and reproducibly for significant periods of time (10 to 15 hours), and can be quickly refurbished for reuse. We have since used the Penning discharge and the IC FT spectrometer to improve wavelength and f -value data for Fe II and Fe III.

3. Fe II and Fe III Wavelengths and f -values

We have used our Penning discharge source to obtain high signal/noise ratio Fe III spectra for the 175 nm to 210 nm region (see Fig. 1). The data analysis procedure used the wavelengths of Nave *et al.* (1997) and Ekberg (1993) for identification of Fe II and Fe III lines, respectively. Because the wavelengths of Nave *et al.* (1997) are very accurate, our new wavelengths for the ~ 400 lines identified as Fe III have uncertainties of about 0.2 m\AA (about one part in 10^7). They therefore supplant those of Ekberg (1993) for the needs of modern high resolution astronomical spectroscopy.

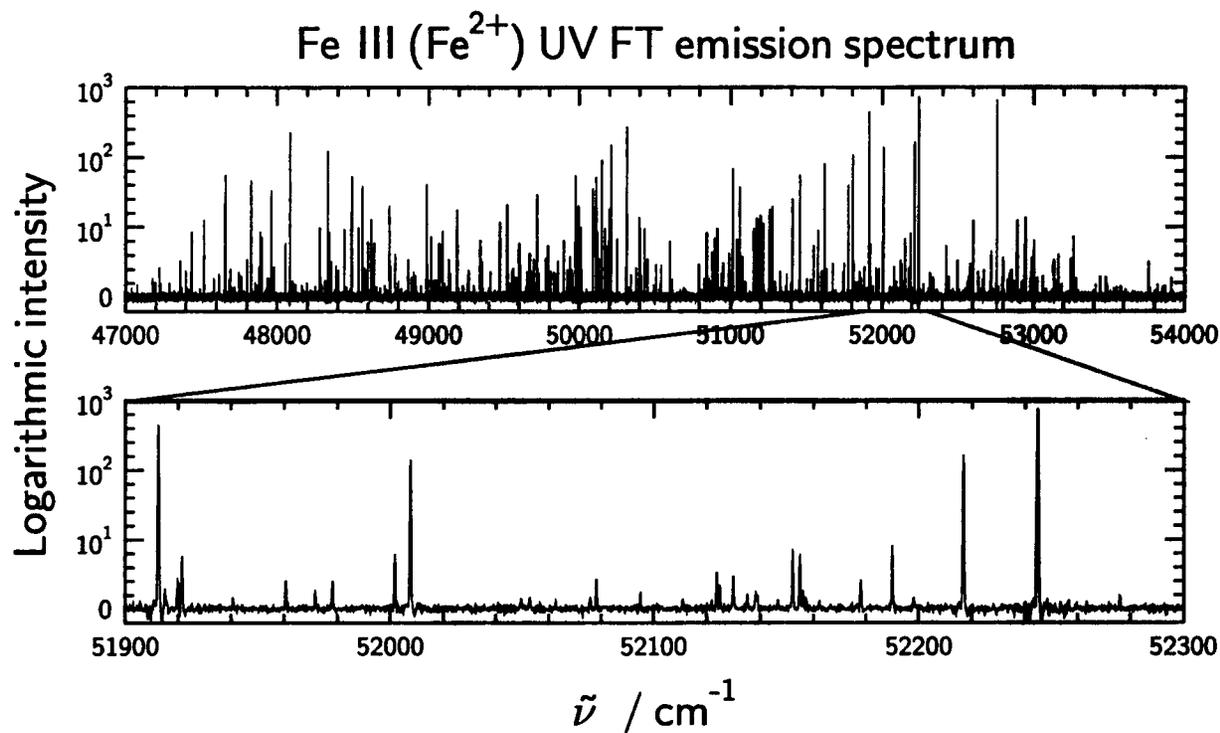


Fig. 1.— Top: Spectrum from 1851.8 to 2127.7 Å;
 Bottom: A 15 Å portion of the spectrum centered at ~1919 Å.

Our measurements of the spectrum of Fe III have been accompanied by contemporaneous determinations of the radiometric response of the FT spectrometer. Thus, branching fractions are determined and A -values could be calculated if lifetimes were available.

The hollow cathode discharges used for the precision spectroscopy of Fe II (Nave *et al.* 1997) do not excite the higher-lying levels of Fe II. However, our Penning discharge does and we have taken advantage of this feature to make new measurements of A -values for Fe II (Pickering *et al.* 2001). This work required determining the responsivity of the FT spectrometer using a standard D_2 emission source, so that accurate branching fractions, and thus relative f -values, can be derived from the spectral data.

When the Fe III work is complete, we will extend our efforts to other doubly charged ions of the iron group, initially Co III and then Cr III, Ni III, and Mn III. All three ions have spectra that are significant components of data obtained by *GHR*S, *STIS*, and *FUSE*. The second spectra of these atoms may also be worthy of additional study. For example, we believe that the Penning discharge will excite levels in Co II that were not observed by Pickering *et al.* (1998), and, therefore, that additional wavelengths and f -values can be measured.

Acknowledgments

This work was supported in part by NASA Grant NAG5-4348 to Harvard University, PPARC of the UK, and a NATO Collaborative Research Grant. JCP is supported by a Royal Society University Research Fellowship. The authors thank D. S. Leckrone, G. Nave, and W. H. Parkinson for encouragement and assistance.

REFERENCES

- Ekberg, J. O., 1993, *A&AS*, **101**, 1.
Nave G., S. Johansson & A. P. Thorne, 1997, *JOSA B*, **14**, 1035.
Pickering, J. C., 1999, *Physica Scripta*, **T38**, 27-34.
Pickering, J. C., A. J. J. Raassen, P. H. M. Uylings & S. Johansson, 1998, *ApJS*, **130**, 541.
Pickering, J. C., S. Johansson & P. L. Smith, 2001, *A&A*, **377**, 361.
Smith, P. L., *et al.*, 1998, in *Improved VUV Spectroscopy of Doubly Ionized Atoms*, APS Conf. Ser. **143**, 395.
Thorne, A. P., C. J. Harris, I. Wynne-Jones, R. C. M. Learner & G. Cox, 1987, *J. Phys. E.*, **20**, 54.
Thorne, A. P., G. Cox, P. L. Smith & W. H. Parkinson, 1994, *Proc. SPIE*, **2282**, p.58.